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## THEORETICAL ASPECTS OF THE DYNAMIC BEHAVIOR OF CAR-TRAILER COMBINATIONS WITHOUT BRAKING SYSTEMS DURING THE BRAKING PROCESS

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**Abstract:** This paper theoretically analyzes the problem of braking car-trailer combinations in the case of trailers without braking systems. The study identifies the factors that influence the dynamic behavior of these combinations, with a special focus on the role of trailers without braking systems. The main objectives of the research are to evaluate the impact of trailer loading on stability and braking distance, to analyze the interactions between the tractor vehicle and the trailer during braking and turning, and to formulate recommendations for optimizing the safety of tractor-trailer assemblies. Mathematical models and simulations are also used to evaluate the dynamic behavior of the assembly in various loading scenarios. The results highlight the fact that the load distribution in the trailer has a significant impact on the stability of the assembly and the braking-distance. Non-uniform loading can lead to dangerous imbalances, especially during braking and turning maneuvers. In conclusion, this paper offers an in-depth analysis of the factors that influence the dynamic behavior of tractor-trailer assemblies, providing valuable information for improving their safety and performance.

**Key words:** vehicle dynamics, trailers, braking, stability, loading, road safety, European standards.

### 1. INTRODUCTION

Automobile braking systems constitute a fundamental aspect of vehicle safety, significantly contributing to speed regulation and the prevention of collisions. The effectiveness of these mechanisms is influenced by various factors, including the weight of the vehicle and the prevailing road conditions [2], what kind and how good the tires are [3], and how someone drives [4, 5]. EU Regulation 2018/858 [6] sets out how land vehicles are categorized, highlighting why it's important to define the different ways they're used when talking about road safety.

The design of contemporary braking mechanisms constitutes a complex task that necessitates technological advancements across multiple engineering disciplines, including materials science and engineering, mechanical engineering, electronic engineering, and information technology [7, 8].

Braking mechanisms can be categorized according to their activation methods—namely mechanical, pneumatic, hydraulic, and combined—as well as their structural design (disc or drum) [9]. Disc braking mechanisms are widely used because they work better in different stopping situations and have thermal advantages compared to drum mechanisms [10, 11].

Wear of brake discs and pads is an inevitable occurrence, influenced by things like how the braking mechanism is used, driving style, vehicle weight, the materials used, and environmental conditions [19]. Overheating is a major issue that affects brake discs, potentially reducing stopping effectiveness and damaging the system [22]. Other common problems with brake discs include cracking, becoming out-of-round, and vibrations [21, 22, 23, 34].

Examining the braking mechanisms is essential for ensuring the vehicle operates efficiently and safely. This process involves regularly inspecting components, replacing worn parts, and identifying any potential issues

[25, 26, 27]. The advancement of predictive maintenance technologies, which rely on the analysis of data gathered from the vehicle, holds the potential to enhance maintenance procedures and reduce costs [28 - 32].

The safety of car-trailer combinations constitutes a substantial engineering challenge due to the intricate dynamic interactions between the towing vehicle and the attached load. Unlike independent vehicles, articulated units are particularly vulnerable to instabilities such as jackknifing and trailer sway, especially during heavy braking maneuvers, when the trailer's momentum may exceed the braking capacity of the towing vehicle.

The additional weight of the trailer significantly alters the vehicle's dynamics, impacting stopping distance, stability, and handling ease. Furthermore, European regulations do not mandate braking systems for trailers classified as category O1 (those with a maximum permissible weight of 0.75 tons), so the braking efficiency of the car-trailer combination relies exclusively on the braking mechanism of the towing vehicle. Mass distribution on the trailer being very important for stability and avoiding uncontrolled oscillations of the combination [33-35].

Current research shows a constant focus on making braking mechanisms better, but there are still gaps in fully understanding the complex dynamic interactions between a vehicle and a trailer without its own brakes, especially regarding how the trailer's load affects the behavior of the combination. This study is needed to deepen our understanding of these phenomena and to offer practical advice for the design, testing, and safe use of car-trailer setups. The main originality of this research lies in the detailed analysis of how changes in the trailer's load affect stability and stopping distance, related to current European standards. The main goals of this research are:

- To analyze how a car-trailer setup with unbraked trailers behaves dynamically.
- To assess the impact of different trailer loading scenarios on the dynamic behavior of the setup.
- To determine the specific stopping distance of these setups under various loading conditions.

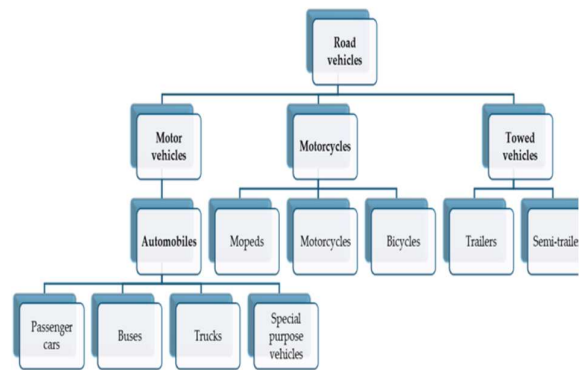
- To develop recommendations for optimizing the safety and stability of car-trailer setups.

## 2. THEORETICAL FOUNDATIONS OF BRAKING SYSTEMS AND THE DYNAMICS OF CAR-TOWING-TRAILER SETUPS

This part lays out the basic ideas about how car braking systems work and looks at how car-towing-trailer combinations behave. The aim is to provide the necessary theoretical groundwork for understanding how these setups act under different operating conditions.

### 2.1 Legal Aspects of Braking Systems

EU Regulation 2018/858 [36] lays down the classification of land vehicles, which includes cars, motorcycles, towed vehicles, and road trains. This classification, shown in Figure 1, defines the different categories of vehicle use, and this has important implications for safety requirements and type approval. ECE-UN Regulation No. 13 [37] sets out consistent requirements for the approval of vehicles in categories M (passenger transport), N (goods transport), and O (trailers) about their braking systems.



**Fig. 1.** Types of land vehicles according to EU Regulation 2018/858 [36].

### 2.2 Operating Principles of Braking Systems

The braking system serves as an essential component for ensuring the safety of both the vehicle and its cargo [1]. An effective braking

system should enable a rapid decrease in speed and allow for gradual deceleration without abrupt jolts.

How well a vehicle brakes is judged by the stopping distance ( $S_f$ ), the stopping time ( $t_f$ ), and the deceleration ( $a$ ). These measures, shown in Figure 2, are affected by how the braking system is activated, how well it performs, the road surface characteristics, and the condition of the tires.

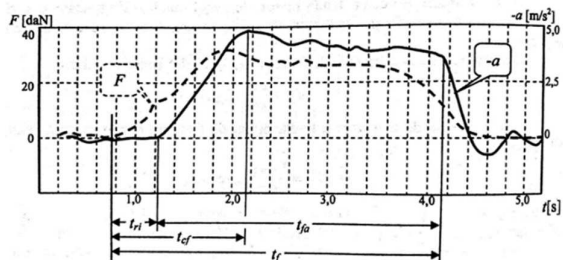


Fig. 2. Parameters of the braking process [38].

Figure 3 shows a simplified diagram of the braking process, used to make calculations easier.

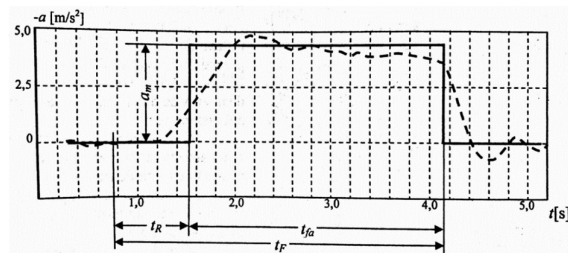


Fig. 3. Simplification of the braking process [38].

### 2.3 Dynamics of Car-Towing-Trailer Setups

Braking a vehicle that is towing a trailer is more complex than braking a single vehicle. Figure 4 shows the system of forces acting on the combined unit, and Figures 5 and 6 detail the forces acting on the car and the trailer, respectively. Equations (1) and (2) describe the balance of forces in vertical and horizontal directions.

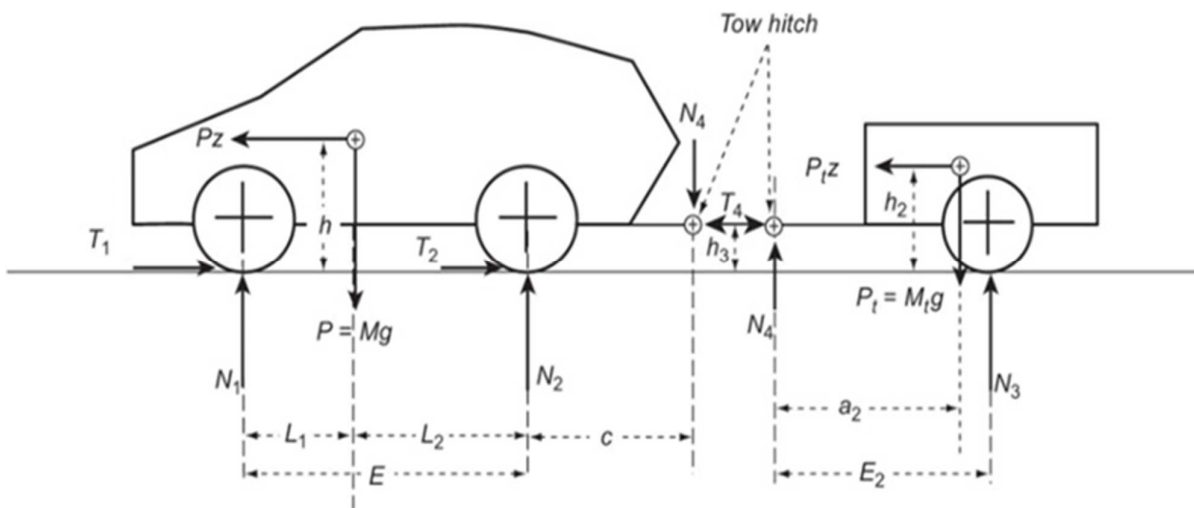


Fig. 4. The combined force system for light vehicles and trailers under dynamic braking conditions [9].

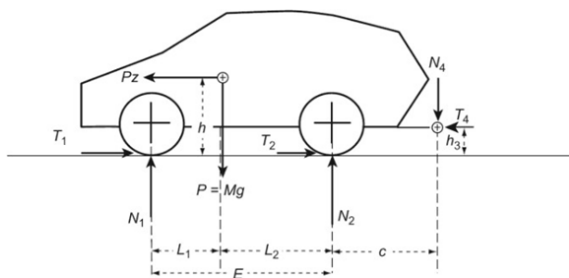


Fig. 5. Forces acting on the car [9]

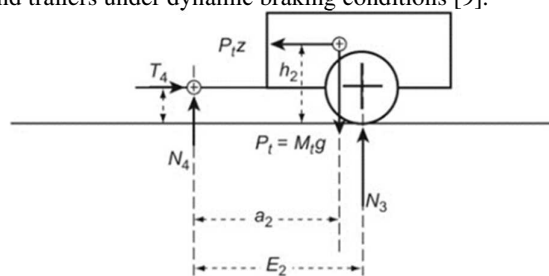


Fig. 6. Forces acting on the trailer. [9]

The parameters represented in the above figures are:

$M_t$  - mass of the trailer (kg),

$P_t$  - weight of the trailer(N),  
 $h_2$  - height of the trailer's center of gravity above the road surface (m),  
 $h_3$  - height of the towing hitch above the road surface (m),  
 $E_2$  - horizontal distance from the trailer hitch to its wheel axle (m),  
 $a_2$  - horizontal distance of the trailer's center of gravity behind the towing hitch (m),  
 $a$  - horizontal distance from the rear axle of the car to its towing hitch (m).

Since the trailer does not have a braking system,  $T_3 = 0$ .

Thus, the system becomes:

Vertically:

$$N_1 - P + N_2 - N_4 = 0, \quad (1)$$

Horizontally:

$$T_1 + T_2 - P_z - P_4 = 0, \quad (2)$$

The mass of the trailer significantly influences the deceleration of the combination. Equation (3) approximates the deceleration when braking with all wheels locked.

Table 1 presents experimental data on measured and calculated deceleration for different masses of the combination.

$$a_c = \frac{W_c \cdot \mu}{(W_c + W_T)} \quad (3)$$

where:

$W_c$  – mass of the car

$W_T$  – mass of the trailer

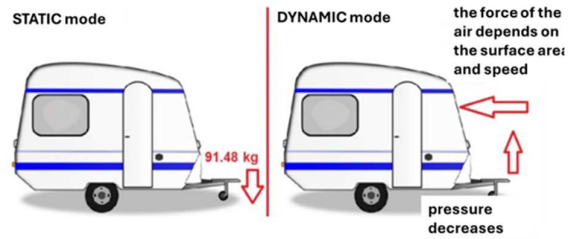
$\mu$ – coefficient of friction.

**Table 1.** Experimental deceleration data [1].

Combination Mass	Measured Deceleration	Calculated Deceleration
15399 N (1570 kg)	0.63	0.65
17401 N (1774 kg)	0.55	0.57
19100 N (1948 kg)	0.5	0.5

## 2.4 General Information Regarding Trailer Loading

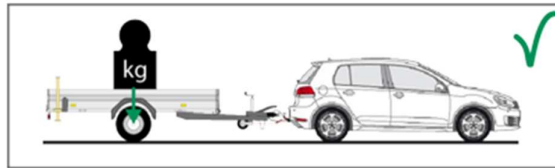
Correctly loading a trailer is vital for safety. Figure 7 shows the loading forces at the trailer hitch, and Table 2 presents the maximum permitted weights. Figures 8, 9, and 10 illustrate the right and wrong ways to load trailers, highlighting how important it is to distribute the load evenly and position the center of gravity correctly.



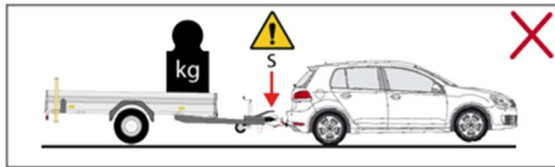
**Fig. 7.** Loading forces at the trailer hitch. [39]

**Table 2.** Maximum weights on the hitch and coupling [40,41].

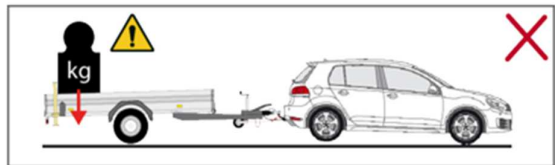
Maximum weight on the hitch according to the car manufacturer's technical spec	100 kN
Maximum weight supported by the hitch according to the hitch manufacturer's spec	150 kN
Maximum weight/load on the coupling indicated by the towed vehicle maker (trailer, caravan)	75 kN



**Fig. 8.** Correct loading with the center of gravity's shortest lever arm [42].



**Fig. 9.** Load distributed towards the front - large vertical load [42].



**Fig. 10.** Load distributed towards the rear – reduced vertical load [42].

## 2.5 Braking Distance of the Car-Trailer Combination

The brake distance is a critical factor for the safety of a car-trailer setup. Equation 4 allow for the calculation of deceleration and braking distance.

$$d_{M+R} = d_M \cdot \frac{P_M}{P_M + P_R} \quad (4)$$

where:

$d_{(M+R)}$  - average deceleration of the car coupled with an unbraked trailer [ $m/s^2$ ];

$d_M$  - maximum average deceleration of the car obtained during a type 0 test with the engine disengaged [ $m/s^2$ ];

$P_M$  - mass of the car (laden);

$P_R$  - maximum mass of an unbraked trailer that can be coupled, according to the car manufacturer's specifications.

The decelerating motion of a vehicle can be described by distance, time, speed, and deceleration. Distance and time are fundamental quantities, while speed and deceleration are derived from distance and time and can be broken down into fundamental quantities. Vehicle deceleration can also be calculated by dividing the change in speed by the time interval over which the speed change occurred. [5]

Thus:

$$\alpha = \frac{\Delta V}{\Delta t} = \frac{V_2 - V_1}{t_2 - t_1} (m/s^2) \quad (5)$$

where:

$t_1$  - start time of deceleration (s);

$t_2$  - end time of deceleration (s);

$V_1$  - speed at the beginning of deceleration [ $m/s$ ];

$V_2$  - speed at the end of deceleration [ $m/s$ ].

The approximate stopping distance of a car moving in a straight line can be determined with the relation:

$$d = 0.039 \cdot \frac{V^2}{a} \quad (6)$$

where:

$d$  - braking distance [ $m$ ];

$V$  - speed [ $km/h$ ];

$a$  - deceleration [ $m/s^2$ ].

## 2.6 Theoretical Calculations

To calculate the impact of a 750 kg trailer (loaded) on standard towing vehicle with a mass of 1500 kg, we take into consideration that tire-road friction coefficient is  $\mu = 0.7$ , dry pavement and realistic for many cars, no reaction time included (pure braking distance only) and gravity  $g = 9.81 m/s^2$ .

The trailer brakes activate automatically from drawbar push during deceleration. Properly adjusted systems typically allow the full combination to achieve 6.0–7.0  $m/s^2$ .

The results are described in table 3.

**Table 3.** Results of theoretical calculations.

Trailer mass (kg)	Total mass (kg)	Deceleration ( $m/s^2$ )	Stopping distance 60 km/h (m)	Stopping distance 100 km/h (m)
0	1500	6.87	20.2	56.2
100	1600	6.48	21.4	59.5
400	1900	5.57	25	69.3
500	2000	5.32	26.1	72.5
650	2150	5	27.8	77.2
700	2200	4.9	28.3	78.7
750	2250	4.81	28.9	80.3

The position of the load on the trailer significantly affects towing safety, stability, braking performance, and stopping distances — often more dramatically than just the total trailer mass.

Widely accepted industry standard for safe towing with most passenger vehicles and trailers is aiming for 10–15% of the trailer's total loaded mass on the tongue.

This is achieved by placing roughly 60% of the load's weight forward of the trailer axle(s) and 40% behind (the classic "60/40 rule" for many single-axle trailers).

**Table 4.** Effects of Incorrect Load Position

Load Position	Tongue Weight (% of trailer mass)	Approx. Max Deceleration	Stopping Distance 100 km/h	Change vs. Ideal Loading
Ideal (60/40 rule)	10–15%	~0.49–0.55 g	~78–80 m	Baseline
Slightly too forward	18–22%	~0.42–0.47 g	~85–95 m	+10–20% longer
Very too forward	>22–25%	~0.38–0.44 g	~95–110 m	+20–40% longer
Slightly too rearward	5–9%	~0.40–0.48 g	~85–100 m	+10–25% longer
Very too rearward	<5%	~0.30–0.42 g	100–130 m	+30–60%

## 3. RESEARCH METHODOLOGY

This section outlines the methodological approach adopted in this study to analyze the dynamic behavior of car-towing-trailer setups. The methodology combines theoretical elements with the analysis of existing data, focusing on the factors that influence the safety and performance of these combinations.

### 3.1 Theoretical Analysis of Braking Systems and the Dynamics of Car-Towing-Trailer Setups

Relevant European regulations were analyzed, particularly EU Regulation 2018/858 [36] and ECE-UN Regulation No. 13 [37], to understand

the safety and approval requirements applicable to the brake systems of cars and trailers. The operating principles of braking systems were also studied, with a focus on the parameters of the braking process (braking distance, braking time, deceleration) and the factors influencing their performance.

Some theoretical calculations were developed to describe the dynamic behavior of car-towing-trailer setups during braking. The model considers the forces and moments acting on the towing vehicle and the trailer, their interaction through the towing hitch, as well as the influence of the trailer's mass and load distribution.

### 3.2 Analysis of Experimental Data and European Standards

Experimental data on the braking distance of car-trailer combinations, obtained from previous studies [1], were analyzed to evaluate the influence of the trailer's mass on braking performance.

The results of the theoretical analysis and the experimental data were compared with the relevant requirements of European standards regarding the approval and testing of braking systems for car-trailer combinations. Compliance with ECE-UN Regulation No. 13 [37] was analyzed.

## 4. RESULTS AND DISCUSSIONS

This section presents the results obtained from the analysis of the dynamic behavior of car-towing-trailer setups and discusses the implications of these results in the context of road safety and current regulations.

### 4.1 Impact of Trailer Loading on Dynamic Behavior

The analysis of braking distance as a function of trailer loading highlights an increase in braking distance as the towed mass increases. This result is consistent with basic physical principles, where a larger mass requires a greater braking force to achieve the same deceleration.

Furthermore, the distribution of the trailer's load has a significant impact on the braking distance. Uneven loading, with a concentration of mass at

the rear of the trailer, for example, can reduce the stability of the combination and lengthen the braking distance.

Figure 7 graphically illustrates the loading forces at the trailer hitch, emphasizing the importance of respecting the values recommended by manufacturers.

Moreover, Figures 8, 9, and 10 visually demonstrate the impact of load distribution on stability. Correct loading, with the trailer's center of gravity positioned as low as possible and above the axle (Figure 8), ensures optimal stability, while loading predominantly at the rear (Figure 10) reduces the vertical load on the hitch and can cause instability.

### 4.2 Comparison with European Standards

The results obtained are compared with the relevant requirements of European standards regarding the approval and testing of braking systems for car-trailer combinations. ECE-UN Regulation No. 13 [37] establishes uniform requirements for the approval of vehicles in categories M, N, and O regarding braking.

Specifically, the study's results are reported in relation to the limit values for braking distance and average deceleration.

Significant deviations between experimental and theoretical values may indicate the need for adjustments to the mathematical model or the consideration of additional factors influencing the dynamics of the combination.

### 4.3 Practical Implications of the Results

The results obtained have significant practical implications for the design, testing, and use of car-towing-trailer setups. Based on these results, the following recommendations are made:

**Optimal loading of trailers:** To ensure stability and minimize braking distance, a uniform distribution of the load over the trailer's surface is recommended, with the center of gravity positioned as low as possible and above the axle. The maximum permissible vertical load limits on the towing hitch, specified by the manufacturers of the vehicles and towing hitches (Table 2), must be observed.

**Selection of the appropriate towing vehicle:** The towing vehicle should be selected based on the

maximum mass of the trailer it can safely tow. It is essential to consider the capacity of the towing vehicle's braking system to dissipate the additional kinetic energy generated by the trailer's mass.

In addition to what has been mentioned, the following figures illustrate aspects related to braking distance. Specifically:

Figure 11 shows the braking distance for a car with a trailer, highlighting the significant increase in braking distance when towing an unbraked trailer.



Fig. 11. Braking distance with a trailer without a braking system.

On the other side, figure 12 highlight the braking distance for a trailer with a braking system, demonstrating the effectiveness of trailer braking systems in reducing stopping distance and improving the stability of the combination.



Fig. 12. Braking distance with a trailer with a braking system.

These figures underscore the importance of trailer brake systems for the safety of car-towing-trailer combinations and the need to comply with European standards governing the performance of these systems.

## 5. CONCLUSIONS

Based on the results obtained, the following conclusions can be drawn:

At 100 kg trailer, only ~6% longer stopping distance (very minor penalty) is observed.

At 400–500 kg, already 23–29% longer distances — noticeable in emergency braking

At 650–700 kg → 37–40% increase — significant safety degradation.

At 750 kg (legal unbraked limit in many countries) ~43% longer distances are obtained.

Physics of weight transfer and tire loading: During braking, most stopping force comes from the front tires of the tow vehicle (often 60–70%+ due to forward weight shift). Excessive tongue weight unloads the front axle → reduced front grip → lower overall deceleration. Low tongue weight causes instability/sway → driver must modulate brakes → effective stopping distance increases.

So, in conclusion, adding a trailer (400–750 kg) to a 1,500 kg vehicle reduces maximum deceleration and increases braking distances by 23–43 % when unbraked.

However, load position has an even bigger effect and when the load is correct (10–15 % tongue weight, 60 % of load forward of the axle) keeps performance close to the calculated values.

When the load has a wrong position (too far forward or too far back) can add another 10–60 % to stopping distance — or cause dangerous sway and loss of control.

Total mass matters, but proper load placement is the most critical safety factor.

Drivers towing trailers must be aware of the specific characteristics of driving these combinations and adopt a defensive driving style, anticipating maneuvers and maintaining larger safety distances.

Future research will focus on the development of advanced braking assistance systems, specially adapted for car-towing-trailer combinations, to compensate for the negative effects of the trailer's mass and loading on stability and braking distance.

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## **Aspecte teoretice ale comportamentului dinamic al combinațiilor autoturism-remorcă fără sistem de frânare în timpul procesului de frânare**

Această lucrare analizează teoretic problema frânării ansamblurilor autoturism-remorcă în cazul remorcilor fără sisteme de frânare. Studiul identifică factorii care influențează comportamentul dinamic al acestor combinații, cu accent special pe rolul remorcilor fără sisteme de frânare. Principalele obiective ale cercetării sunt evaluarea impactului încărcării remorcii asupra stabilității și distanței de frânare, analizarea interacțiunilor dintre vehiculul tractor și remorcă în timpul frânării și virajelor și formularea de recomandări pentru optimizarea siguranței ansamblurilor autoturism-remorcă. De asemenea, sunt utilizate modele matematice și simulări pentru a evalua comportamentul dinamic al ansamblului în diverse scenarii de încărcare. Rezultatele evidențiază faptul că distribuția sarcinii în remorcă are un impact semnificativ asupra stabilității ansamblului și a distanței de frânare. Încărcarea neuniformă poate duce la dezechilibre periculoase, în special în timpul manevrelor de frânare și virare. În concluzie, această lucrare oferă o analiză aprofundată a factorilor care influențează comportamentul dinamic al ansamblurilor autotractor, oferind informații valoroase pentru îmbunătățirea siguranței și performanței acestora.

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